

DILEPTON EMISSION AT TEMPERATURE DEPENDENT BARYONIC QUARK-GLUON PLASMA

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A fireball of QGP is evolved at temperature dependent chemical potential by a statistical model in the pionic medium. We study the dilepton emission rate at temperature dependent chemical potential (TDCP) from such a fireball of QGP. In this model, we take the dynamical quark mass as a finite value dependence on temperature and parametrization factor of the QGP evolution. The temperature and factor in quark mass enhance in the growth of the droplets as well as in the dilepton emission rates. The emission rate from the plasma shows dilepton spectrum in the intermediate mass region (IMR) of (1.0 – 4.0) GeV and its rate is observed to be a strong increasing function of the temperature dependent chemical potential for quark and antiquark annihilation.

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I. INTRODUCTION

The ongoing experiments like ultra-relativistic heavy-ion collision at BNL and the large hadron collider at CERN have focussed on the search of the QCD phase structure and the formation of mini big bang. The experiments at BNL and CERN will provide the best platform to study the creation and evolution of such mini big bang called Quark-Gluon Plasma (QGP), which is perhaps believed to be formed in the expansion of the early universe [1]. Since we believe that the matter existed only for a few microseconds after the big-bang, its direct detection is very difficult even in these experiments. There are indirect possibilities for detection like strangeness enhancement [2], J/ψ suppression [3] and radiation of dileptons and photons [4–6] etc. Among these indirect probes, dileptons and photons are considered to be the most promising signals for its detection of QGP formation created in relativistic heavy-ion collision (RHIC). It is due to the fact that the dilepton driving out of the collisions among the quarks, antiquarks and gluons brings the whole informations about the existence of the plasma fireball and tell the properties of the fireball to the detector. They interact through electromagnetic force due to the large mean free path in their production. In order to see the production of dilepton for the signal of QGP formation, we look at the process of annihilation of quark and antiquark and they produce virtual photons which subsequently decay into dileptons such as l^-l^+ , $\mu^+\mu^-$.

Many theoretical and experimental researchers have calculated dilepton and photon emissions at finite temperature and at quark chemical potential. The experiments at AGS and SPS energies [7] have reported the presence of significant amount of baryon chemical potential and even at RHIC energies $\sqrt{s} \leq 200$ AGeV there has been the detection of such baryon chemical poten-

tial. These informations indicate [8, 9] that the colliding heavy ions may not be fully transparent in the centrality region of the colliding particles and the region may have significant amount of dense nuclear matter. The work of Hammon and coworkers [10] supported these arguments of existing the chemical potential and predicted the initial nonequilibrium QGP produced at RHIC energies, indicating that the system has finite baryon density or chemical potential. So, in the theoretical study, dilepton emissions in finite baryonic chemical potential has been calculated through various distribution functions and perhaps, the work of Dumitru et al. [11] gives the first signal of dilepton emission at finite baryonic chemical potential with Fermi distribution functions. Then this work is further studied by Strickland using quark and gluon fugacities in jüttner distribution function. He showed another promising result calculated from the non-equilibrium quark-gluon plasma [12]. The recent work of Majumder et al. [13] have indicated the emission of dileptons from QGP at the RHIC energies at finite baryon density. Bass et al. [14] idea of parton rescattering and fragmentation leads to a substantial increase in the net-baryon density at midrapidity region. Besides these works, we have the reports of other authors on dilepton production at low mass region [15]. These works suggest the importance of chemical potential in the dilepton calculation. To produce such emission, we consider the system in the pionic medium in which the equilibrium thermodynamic QGP is a function of temperature T and chemical potential μ and the potential itself as function of temperature.

In this brief article, we choose the baryonic chemical potential which is considered to be temperature dependent chemical potential (TDCP) and the value has a change on the quark and antiquark distribution functions. We take the value of the chemical potential in the scale of QCD parameter of dense nuclear matter. The chemical potential considered is obtained through [16]:

$$\mu(T) = 2\pi\beta^{-1}\sqrt{1 + \frac{1}{\pi^2}\ln^2\lambda_q} \quad (1)$$

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where $T = \frac{1}{\beta}$ taken in the scale of QCD and $\lambda_q = e^{\frac{\mu_q}{T}}$ is quark fugacity. However, we consider the massless dynamical quark as a finite value and it is called thermal dependent quark mass (TDQM) obtained through the parametrization value and temperature. The finite value of the quark mass is defined as

$$m_q^2 = \frac{8\pi}{(33 - 3n_f)} \frac{T^2}{\ln(1 + (\frac{\gamma N^{\frac{1}{3}} T^2}{2\Lambda^2})^{\frac{1}{2}})} \quad (2)$$

with the QCD parameter $\Lambda = 150 \text{ MeV}$ and normalising $N = \frac{16\pi}{27}$. γ is parametrization factor which is like the Reynold's number to take care of the hydrodynamical aspects of the hot QGP flow. Its value is determined in the most effective way of the flow parameter of quarks γ_q and gluons γ_g and it enhances in the growth of free energy of QGP droplet. It is expressed as

$$\gamma = \sqrt{2}(\frac{1}{\gamma_q^2} + \frac{1}{\gamma_g^2}) \quad (3)$$

with the value of $\gamma_g = 6\gamma_q$ or $8\gamma_q$ and $\gamma_q = 1/6$ [17].

Using all such parameters, we create the QGP droplet at TDCP incooperating the quark mass as a finite value in the system and look at the improvement produced by the TDCP in the growth of QGP droplet. Then we calculate dilepton emission at the TDCP from such a system of QGP and see its emission rate.

The paper is organised as follows: In Sec.II we recall a brief highlight of the evolution/growth of QGP fireball through the statistical model in the pionic medium. In Sec.III we look at the dilepton emission and integrated yields at temperature dependent chemical potential (TDCP). In the last Sec.IV we conclude and present our results.

II. THE FREE ENERGY GROWTH OF QGP DROPLET AT TDCP

We use the statistical model at the TDCP for the growth of QGP droplet in the pionic medium. The system is considered to be constituted by the free quarks, antiquarks, gluons and pions. We construct the free energies of the particles using the model of mean field potential in their density of state. The constructed free energies of these noninteracting fermions and bosons at the temperature dependent chemical potential are defined as F_i in which contribution of quarks and gluons are indicated by the upper sign or bosons by the lower sign. It is expressed as:

$$F_i = \mp T g_i \int dp \rho(p_i) \ln(1 \pm \exp(-\sqrt{m_i^2 + p_i^2} + \mu/T)) \quad (4)$$

where g_i is the appropriate colour and particle-antiparticle degeneracy factor. Its value is taken as 6 and 8 for quarks and gluons [18]. $\rho(p_i)$ is the density of states of the particular particle i (quarks, gluons) based

on the effective potential among the interacting particles and it is defined within the range of momentum space dp_i in a spherically symmetric system. It is given by [19]

$$\rho(p_i) = v/\pi^2 [(-V_{eff}(p))^2 (-\frac{dV_{eff}(p)}{dp})] \quad (5)$$

where, $V_{eff} = (1/2p)\gamma g^2(p)T^2 - m_0^2/2p$, known as mean field effective potential among the quarks, antiquarks and quarks-gluons. $g^2(p)$ is the first order QCD running coupling constant. It is given by

$$g^2(p) = (4/3)(12\pi/27)[1/\ln(1 + p^2/\Lambda^2)] \quad (6)$$

The free energy of pion contributed to the total free energies of quarks and gluons is given as:

$$F_\pi = (3T/2\pi^2)v \int_0^\infty p_\pi^2 dp \ln(1 - \exp(-\sqrt{m_\pi^2 + p_\pi^2}/T)) \quad (7)$$

The contribution of the pion energy is due to the fact that the transformation of the phase is slightly dominated by the pions over the other hadronic particles. In addition to these free energies there is another contribution to the total free energy and it takes the role of bag constant in confining the system. It is called the interfacial energy given by [20]

$$F_{interface} = \frac{1}{4} R^2 T^3 \gamma \quad (8)$$

. Therefore, the total energy of QGP fireball is:

$$F = \sum_j F_j \quad (9)$$

where j stands for the different particles viz quark, gluon, pion and interface. The free energy can indicate the nature of QGP fireball evolution and its transition. It also explains the creation of the plasma formation with the size of the droplets.

III. DILEPTON EMISSION AT TDCP FROM QGP

The calculation of dilepton emission at finite temperature and at finite baryon chemical potential have been done by many authors. These calculations are performed on the basis of the expected results coming out from the heavy-ion collision experiments. The experiments expect more productions of lepton than of other particles produced. The possible sources of dilepton are from the annihilation $q\bar{q} \rightarrow l^+l^-$, compton like scattering, $q(\bar{q})g \rightarrow q(\bar{q})l^+l^-$ and $gg \rightarrow q\bar{q}l^+l^-$ fusion processes. Among the processes, Drell-Yan reaction is mostly used for thermal emission of dilepton pairs [21] and the compton scattering such as $q(\bar{q})g \rightarrow q(\bar{q}) + l^+l^-$ follows after Drell-Yan reaction. In this article, we exclusively engage in quark-antiquark annihilation such as $q\bar{q} \rightarrow l^+l^-$ reaction for the dilepton emission. This is due to fact that

it produces larger amount of lepton pair in comparison to the other collisions. In the process, we consider only the dominant production of dilepton in the intermediate mass region neglecting the dilepton spectra from the low mass region. This is fact that the contribution of dilepton through the decay of mesons in the system is negligence. So the dilepton emission rate produced $\frac{dN}{d^4x}$ is given by [22]:

$$\frac{dN}{d^4x} = \int \frac{d^3p_1}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} n_q(p_1, \mu) n_{\bar{q}}(p_2, \mu) \times v_{q\bar{q}} \sigma_{q\bar{q}}(M^2) \quad (10)$$

where,

$$n_q(p_1, \mu) = \frac{\lambda_q}{\exp\left(\frac{p_1 - \mu}{T}\right) + \lambda_q}, n_{\bar{q}}(p_2, \mu) = \frac{\lambda_{\bar{q}}}{\exp\left(\frac{p_2 + \mu}{T}\right) + \lambda_{\bar{q}}} \quad (11)$$

are Fermi-Dirac distribution functions for quarks and antiquarks [23] with their corresponding parton fugacities $\lambda_{q(\bar{q})} = e^{\frac{\mu}{T}}$. For gluon, the Bose-Einstein distribution function is:

$$n_g(p, \mu) = \frac{\lambda_g}{\exp\left(\frac{p}{T}\right) - \lambda_g} \quad (12)$$

with parton gluon fugacity λ_g . The function for gluon can be used in the collision of $q\bar{q} \rightarrow l^+l^-$ or gg fusion reaction. $v_{q\bar{q}}$ is the relative velocity of annihilating quark pair and p_μ is lepton pair four momentum. ($M^2 = p^\mu p_\mu$ invariant lepton pair mass). $\sigma_{q\bar{q} \rightarrow l\bar{l}}$ is the electromagnetic annihilation cross section. Substituting the distribution functions for quark and antiquark in the equation (10) using (11), and integrate over q and \bar{q} momentum, we obtain dilepton emission rate at TDCP as:

$$\frac{dN}{dM^2 d^4x} = \frac{5\alpha^2}{18\pi^3} T M e^{4\sqrt{\pi^2 + \ln^2 \lambda_q}} \times \left(1 + \frac{2m_q^2}{M^2}\right) K_1(M/T) \quad (13)$$

In the above solution, $K_1(M/T) = G(z)$ which is known as the modified Bessel's function and volume element is $d^4x = d^2x_T dy \tau d\tau$. We expand longitudinally the above expression and finally we have emission rate as:

$$\frac{dN}{dM^2 dy} = \frac{5\alpha^2 R^2}{18\pi^2} M \left(1 + \frac{2m_q^2}{M^2}\right) \times \int e^{4\sqrt{\pi^2 + \ln^2 \lambda_q}/T(\tau)} G(z, \tau) T(\tau) \tau d\tau \quad (14)$$

where, $T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3}$.

IV. RESULTS AND CONCLUSIONS

The results of evolution of QGP fireball are shown in the figures (1 – 3). Figure (1) shows the evolution of free

energy at zero chemical potential at the parametrization value of $\gamma_q = 1/6$, $\gamma_g = 6\gamma_q$. It shows very much stability in the formation of droplets for the various values of temperature. Figure (2) shows the change of evolution of the free energy for these various values of chemical potential and indicate the decreasing size of droplets with the increasing chemical potential. The figure (3) shows the change of free energy with the size of droplet at temperature dependent chemical potential with the finite value of quark chemical potential $\mu_q = 47 MeV$. The result indicates that the evolution of QGP through the model has first order shift at the temperature $T = (150 - 170) MeV$ with the increase of chemical potential and the size of the droplet is increased with the increase of the chemical potential. It implies that the evolution of QGP droplet is enhanced with the effect of temperature dependent chemical potential. Moreover the shift in the first order is further explained in figure (4) by the behaviour of the entropy v/s chemical potential. There is a clear jump in the continuity of the entropy curve at the chemical potential $\mu = (990 - 1005) MeV$ at which we found the corresponding temperature as $T = (150 - 170) MeV$.

In figure (5), we show dilepton emission for various values of initial temperature T_0 and at transition temperature $T_c = 0.17 GeV$ without the chemical potential and compared the results with other theoretical calculations of dilepton emission at $\mu = 0$. The results are same over the range of lepton pair mass M . In the figure (6), we show the comparison of emission rates of dilepton at the temperature dependent chemical potential and at finite chemical potential. The emission rate increases with the increase of temperature dependent chemical potential at the transition temperature $T_c = 0.17 GeV$ over the finite chemical potential. The emission rate is much higher at the temperature dependent chemical potential than the emission at finite chemical potential.

Now, if we look dilepton yields with the change of the lepton pair mass in above figures of dilepton production, we obtain a sudden fall in the production rate of dilepton with increase in lepton pair mass M upto $3 GeV$. It indicates that at higher lepton pair mass more suppression is obtained in comparison to the low mass region.

We look again at dilepton integrated yields with the evolution time of the QGP droplet. The dilepton integrated yield is exponentially increasing with the evolution time and after a certain time, it becomes constant for these different values of chemical potential. The plots are shown in the figures (7 – 8) for the chemical potential with their corresponding initial temperatures at transition temperature $T = 0.17 GeV$. Figure (7) shows the integrated yields at transition temperature $T_c = 0.17 GeV$ without the finite value of chemical potential and again compared the results with other results. They are same at this zero chemical potential. In figure (8), we plot the integrated yield for the temperature dependent chemical potential and finite chemical potential at the transition temperature $T = 0.17 GeV$. The integrated yield is very large as compared to the re-

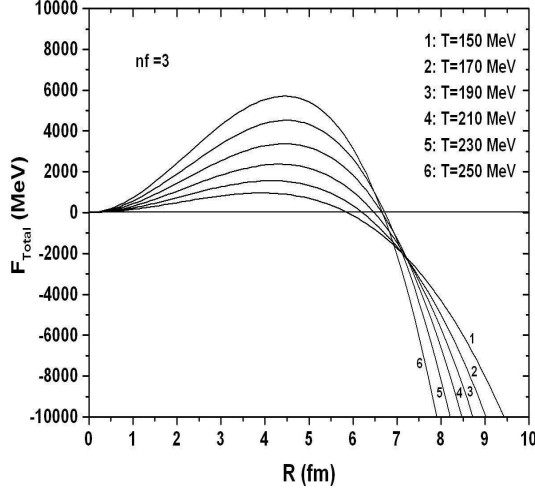


FIG. 1: Free energy with the change of droplet size for various values of temperature.

sults of the earlier work of integrated yeild at finite value

of chemical potential. This is due to the fact that both temperature and chemical potential enhance in the interaction of the particles of the system and yields more dileptons.

Now it indicates that the emission and integrated yield are higher at TDCP as compared to the subsequently fixed value of chemical potential and at zero chemical potential. It means in the QGP phase where the temperature and chemical potential coexist together then the interacions among the partciles are more and dileptons are produced more. So the model with the temperature dependent chemical potential produced improvement over results of finite baryonic chemical potential and zero chemical potential.

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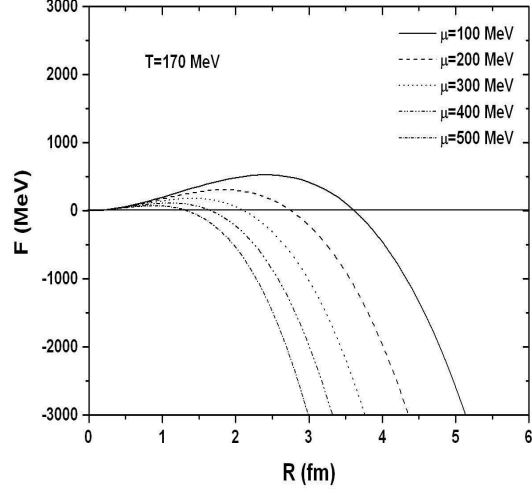


FIG. 2: Free energy with the change of droplet size at the particular transition temperature $T_c = 0.17 \text{ GeV}$ for various values of chemical potential.

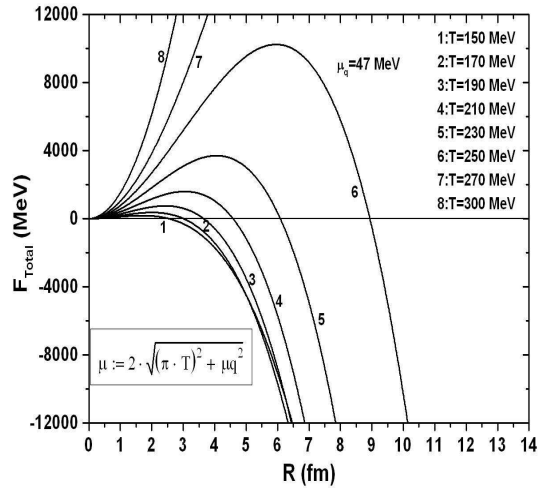


FIG. 3: Free energy with the change of droplet size at the particular quark chemical potential $\mu_q = 0.47 \text{ GeV}$ for different initial temperatures.

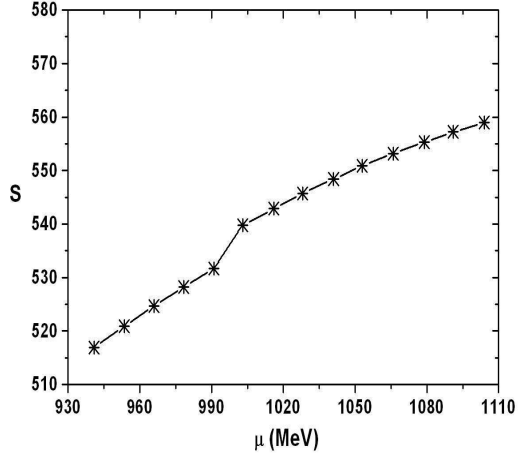


FIG. 4: Entropy v/s , change of chemical potential μ and first order transition at the temperature $T_c = 0.17 \text{ GeV}$.

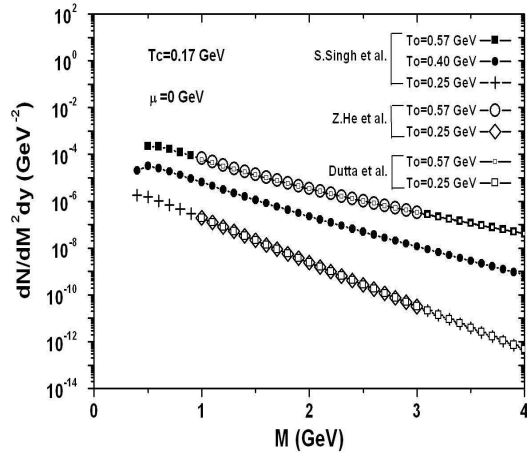


FIG. 5: The dilepton emission rate, $\frac{dN}{dM^2 dy} (\text{GeV}^{-2})$, at transition temperature $T_c = 0.17 \text{ GeV}$ and at zero chemical potential for different initial temperatures and its compared curve.

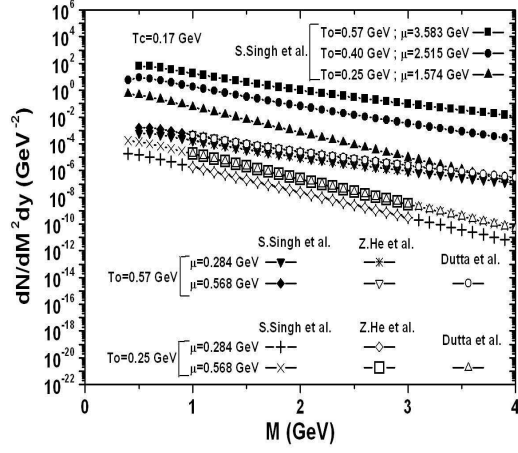


FIG. 6: The dilepton emission rate, $\frac{dN}{dM^2 dy}$ (GeV^{-2}), at transition temperature $T_c = 0.17 GeV$ for the different values of μ with different initial temperatures and its compared curves.

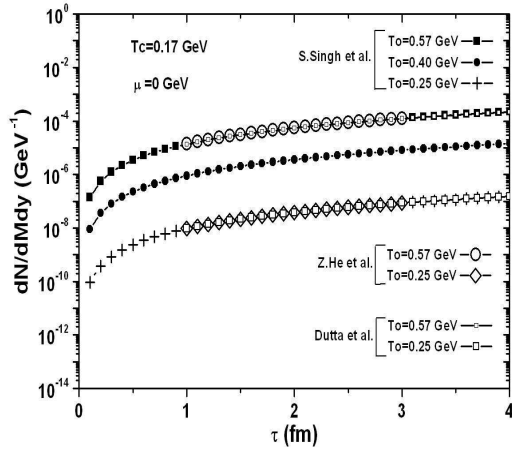


FIG. 7: The dilepton integrated yields, $\frac{dN}{dM dy}$ (GeV^{-1}), at transition temperature $T_c = 0.17 GeV$ and at zero chemical potential ($\mu = 0$) with different initial temperatures and its compared curves.

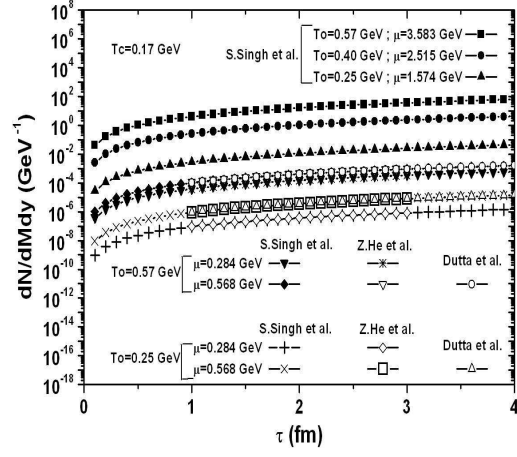


FIG. 8: The dilepton integrated yield, $\frac{dN}{dMdy} \text{ (GeV}^{-1}\text{)}$, at transition temperature $T_c = 0.17 \text{ GeV}$ for the different values of μ with different initial temperatures and its compared curves.